Battery management system employing passive control method

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Article Info

ABSTRACT

A battery management system (BMS) is essential for maintaining peak efficiency and longevity of rechargeable batteries. Conventional battery management system techniques often struggle to monitor, protect, and particularly have difficulties in balancing batteries. The project proposed has introduced a battery management system that employs passive control techniques to address excess energy and overcome these challenges. In the proposed design, a shunt resistor dissipates surplus energy from lithium-ion battery cells into heat following the proposed BMS design. This passive control technique is economically efficient, uncomplicated, and does not require an external power source. A prototype of the proposed BMS design was tested and was able to accurately monitor the battery, dissipate excess energy, and protect the battery while maintaining the cell charge balance. These findings suggest that the proposed BMS has the potential to improve both the effectiveness and longevity of rechargeable batteries.

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1. INTRODUCTION

Lithium-ion batteries have numerous benefits over conventional battery technologies such as lead-acid batteries. Lithium-ion batteries outperform in electric vehicle applications and battery storage uses due to their higher energy density, longer lifespan, and lower self-discharge rates [1]. Their lightweight structure and density were able to minimize vehicle weight, improving traveling distance and acceleration for larger automobiles [2], [3]. Lithium-ion batteries have high capacity without the memory effect, eliminating maintenance, and they preserve energy capacity for a longer period [4], [5]. They are utilized extensively, particularly in electric cars, demonstrating their adaptability and longevity. Nevertheless, they may deteriorate and lose function, such that a battery management system (BMS) will have to be used in order to solve these issues.

A BMS is a crucial component of many electronic devices, from the smallest to the largest, such as electric vehicle (EV) batteries. It maintains the safety and performance of each system and also provides battery condition estimates, cell balance and thermal management of the battery system [6]. BMSs should monitor and regulate characteristics such as state of charge (SOC), state of health (SOH), current, voltage, and temperature of the battery cells [7], [8]. Among these features, SOC estimation is significant for battery life estimation, charge management and cell balancing during charging [9]. A technique utilizing open-circuit voltage (OCV) lookup and additional machine learning models that were able to estimate the SOC of the battery from a BMS itself [10]. Cloud computing and artificial intelligence are being looked into to enhance their capabilities, and this approach enables BMS in processing and predictive modeling to be more accurate and efficient in managing batteries. Several control strategies, such as model predictive control (MPC), have been applied to manage battery charge and discharge schedules effectively, improving the overall battery lifespan and

efficiency [11]. A project in [12] investigates whether this design enhances battery performance and lifespan. A BMS helps with overcharging, over-discharging, temperature changes and battery cell imbalances.

Alternative solutions may be necessary for conventional BMS systems that do not prioritize energy efficiency. This work proposes passive balancing to turn excess power into heat in a battery pack to equalize the energy levels. An effective approach to improve battery performance and lifetime such that many applications can benefit from the inclusion of BMS into the design such as shown in [13] was designed.

The BMS design has three main functions such as monitoring, balancing and protection of the battery. A well-designed BMS should be able to monitor the voltage, current, temperature, SOC, SOH, and power capacity of the battery in which it is being incorporated. The monitoring function within a BMS monitors voltage, current, temperature, and potential risk of fire throughout charging and discharging cycles.

Cell balancing is essential for series-connected battery packs to maintain voltages and charge capacities. It improves energy efficiency and reduces manufacturing tolerances and cell self-discharge, extending the battery life and capacity of the cells [14]-[19]. A comparison of both active and passive cell balancing techniques is shown in Table 1. As the paper suggests, the project was conducted using passive cell balancing in which this approach involves the use of simple resistors in an electric circuit to balance the voltages across the battery, preventing overcharging and under-discharging. The resistors dissipate excess energy into heat in order to maintain the battery cell voltage in passive balancing which this method improves battery pack performance and life expectancy.

The BMS is essential to every system because it maximizes battery capacity and ensures operational safety in which a BMS is crucial to battery system safety and reliability [21]-[24]. These measurements such as voltage, current and temperature, are monitored while safety precautions improve battery performance [25]. An efficient power management technique in wind-battery-assisted hybrid autonomous systems includes a controller that regulates battery charge/discharge cycles and DC bus voltage that prevents overload and deep discharge and maintains smooth functioning [26], [27].

In this paper, a centralized BMS approach has been developed. In a centralized BMS topology, one control unit oversees all battery pack cells, which makes it one of the simplest approaches. The article is organized as follows: i) The methodology and proposed design are demonstrated in section 2; then in ii) Section 3, the proposed BMS design has been tested thoroughly, corresponding to each of its main functions; iii) In section 4, the test results will be discussed in detail for each of the main objectives of the BMS, such as monitoring, balancing and protection; and finally, iv) The conclusion and future works are presented in section 5.

Table 1. Passive control vs active control [20]

Aspect	Passive cell balancing	Active cell balancing
Principle	Make use of a shunt resistor to dissipates excess energy to balance the cell's voltage	Capacitor or inductors that helps in transferring energy from higher to lower voltage cells
Efficiency	Lower efficiency due to energy loss as heat	Higher efficiency as energy is distributed among the cells
Complexity	Simple design with fewer components to be implemented	More complex circuitry requirements and complex system
Cost	Normally lower cost due lesser components	Higher cost due to much more components and advanced control system
Application	Suitable for application that is budget conscious	Used in high performance system that efficiency is critical without considering the cost
Maintenance	Simpler to maintain and lower maintenance cost	Requires more maintenance and higher cost due to its complexity

2.   METHODOLOGY
2.1. Proposed BMS design

A block diagram of the system is proposed, which can be seen in Figure 1. The centralized BMS has been chosen for this project because of the simplicity and stability of the architecture. These sections will provide a detailed overview of the various components and processes involved in the design and act as the foundation for the full functionality of the BMS. Figure 1 below is a block diagram of the proposed system that was implemented, as it shows the fully proposed BMS design that will incorporate some types of sensors, such as current, voltage, temperature and humidity sensors in a centralized BMS topology. All these components will be connected directly to the master controller, in which a node microcontroller unit (NodeMCU) has been used for this project and which will later store collected data while showing real-time parameter readings on the organic light-emitting diode (OLED) display.

2.2. Proposed algorithm of the BMS

The proposed algorithm in Figure 2 was designed for monitoring and maintaining rechargeable battery efficiency and longevity in which, after initializing the system, the cells' voltage, temperature and load current are monitored and determined by the main controller. When the algorithm finds its way to the charging stage,

it balances the cells when the voltage is ≥ 4.1 V after processing the input value and determining the battery voltage. Then, each cell reaches its charging limit during the charging process; the balancing mechanism will be utilized to prevent the battery from overcharging by dissipating extra energy through heat using the balancing resistor. The created algorithm will also stop balancing and charging the batteries if each cell's voltages surpass the limit set before. This approach enables a BMS to balance the necessary cells, guaranteeing maximum battery condition and a long lifespan. Lastly, in the set algorithm for the discharging phase, the cell monitoring algorithm will monitor cell voltage and trigger the cutoff mechanism when it falls below ≤ 2.8 V, preventing any further over-discharge.
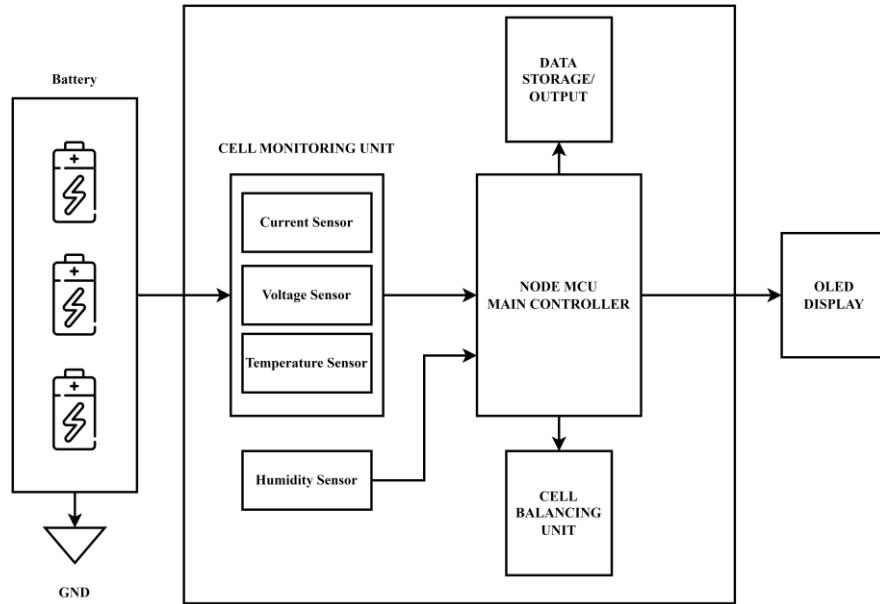

Figure 1. Block diagram of the proposed BMS design
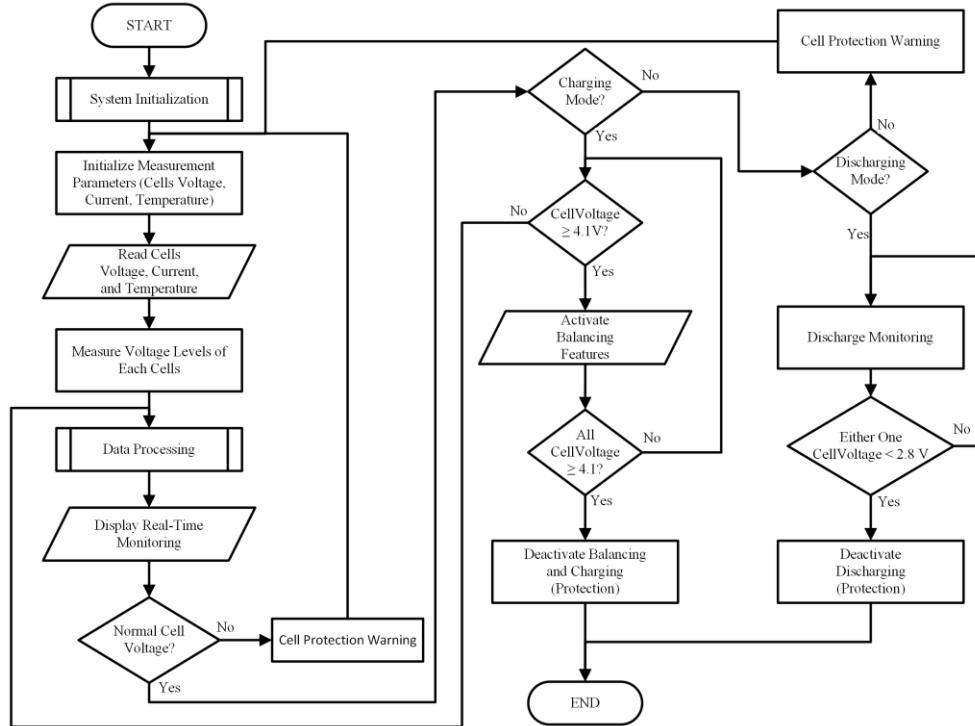
Figure 2. Proposed BMS algorithm

2.3. Proposed BMS working principle

In this section, the working principle of the proposed battery management system (BMS) will be presented. The BMS is designed to perform three key functions: monitoring, balancing, and protection.

2.3.1. Monitoring

The BMS should accurately track and measure battery performance metrics such that these variables include voltage, current, temperature, and SOC for each of the batteries. The BMS captures real-time data utilizing high-precision sensors and monitoring circuits simultaneously. The NodeMCU ESP32 microcontroller monitors the cell's behavior and gathers humidity data from the DH11 sensor, which acts as a supplementary sensor if needed to be implemented in any humid environment. To monitor cell voltage, a voltage divider circuit is used. Two resistors attached to the cell's positive and negative terminals ensure voltage level readings fit within the analog-to-digital converter (ADC) ADS1115's 16-bit precision. ADC transforms voltage divider circuit analog voltage measurements into digital data for NodeMCU ESP32 processing.

The NodeMCU ESP32 is the main controller owing to its programming ease and scalability. It measures cell voltages in real-time using the ADC. After processing using the voltage divider as in (1), these measurements are shown on the OLED display for easy battery monitoring.

$$v_{cell} = \frac{R_2}{R_1 + R_2} \times v_{cc} \qquad (1)$$

2.3.2. Balancing

The balancing aspect of the BMS is a simple technique that utilizes the bleeding resistors to dissipate excess energy from the batteries while charging until each of the batteries is fully charged. The batteries were connected in parallel, and each battery was connected to a bleeding resistor also in parallel to it. This configuration allows for the dissipation of excess energy when the battery reaches a certain voltage threshold, which is set by the algorithm in ESP32 MCU. The purpose of the bleeding resistor is to provide a way for the excess energy to flow and be dissipated, preventing overcharging of the batteries as heat to the surroundings. In order to avoid overcharging, the ESP32 MCU has been set at a 4.1 V upper limit voltage that can mitigate the risk of overcharging in which the main microcontroller ESP32 engages an N-channel metal-oxide-semiconductor (NMOS) transistor when the battery voltage exceeds the particular threshold. This NMOS transistor serves a low resistance pathway, allowing surplus energy to bypass the fully charged battery to each of the assigned bleeding resistors. This approach will dissipate excess energy during charging, preventing overcharging whilst maintaining the battery's voltage below the maximum limit in order to avoid battery swelling and damage. This system requires transferring surplus energy into heat and then allowing it to charge all batteries uniformly and to ensure battery longevity [28], [29].

2.3.3. Protection

The BMS protection approach will ensure battery safety and long-term durability. Battery safety comprises controlled current cutoff when charging or draining at a set threshold in which the two P-channel metal-oxide-semiconductor (PMOS) transistors were utilized as one serving as discharge MOSFET and one for charging MOSFET. The charge MOSFET functions as a switch and blocks off current flow whenever the battery voltage exceeds an algorithm-set threshold during charging. The following prevents overcharging and battery further damage to the cells. Once the battery voltage drops below a predetermined lower threshold during discharging, the discharge MOSFET cuts off current flow to prevent over discharging and preserve battery life. These coupled PMOS transistors provide reliable and effective protection to the BMS which utilizes MOSFETs as the primary relay gate to control battery current flow and maintain safe battery operations.

Each battery system must incorporate intermediate cutoff relays to prevent excessive current from flowing out from cells during the discharging and charging phases. Both of the PMOS transistor intermediate cutoff switches are strategically placed between each battery and the primary bus for the input and output of the battery terminals. The cutoff charging MOSFET engages when a battery hits the maximum voltage threshold, signaling a complete charging for the batteries and this relay stops charging the battery and keeps each cell at its optimal voltage.

2.4. Proposed BMS schematic diagram

Figure 3 displays a proposed schematic diagram for the BMS design in which the diagram was created using EasyEDA web-based EDA tool suite. It is an online platform that facilitates the design, simulation, and creation of PCB designs. The diagram below illustrates the different elements and connections in the design of the proposed BMS, presenting a concise representation of the system's overall structure and utilizing EasyEDA enables the effective and precise creation of the circuit diagram, guaranteeing that the proposed BMS design is both operational and appropriate for this research.
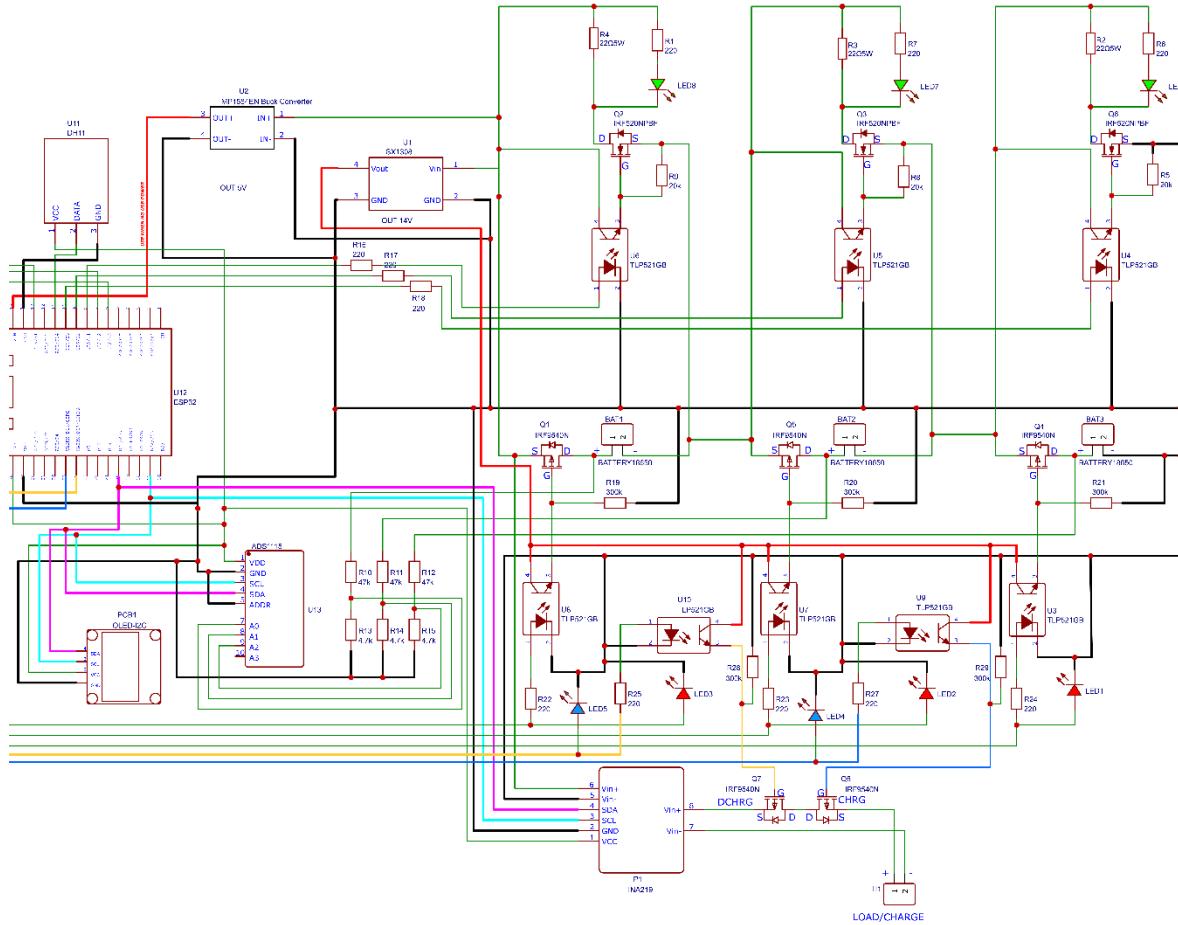
Figure 3. Proposed BMS schematic diagram

2.5. Prototype development of the proposed BMS design

Testing and validation of the system were done using a breadboard prototype at first and then the project proceeded to develop a more durable and compact version of the BMS system using a Veroboard. The components from the breadboard prototype were carefully soldered onto the Veroboard, ensuring accurate placement and secure connections to reduce signal interference. This transition to a Veroboard provided a permanent setup, improving the reliability and longevity of the BMS system. Figure 4 depicts the seamless integration of components on the Veroboard by soldering all the necessary components of the BMS according to the proposed schematics. In Table 2 description for, the list of components used has been described by addressing each of the components with their corresponding alphabets as illustrated for the prototype.

Table 2. Description for Figure 4

| Component	Description
A	ESP32
B	Buck converter
C	Boost converter
D	OLED display
E	INA219 current sensor
F	Cutoff MOSFET
G	ADS1115 ADC
H	DH11 Sensor
I	Cell balancer portion
J	Voltage divider
K	Li-ion battery
L	Connect load/charger
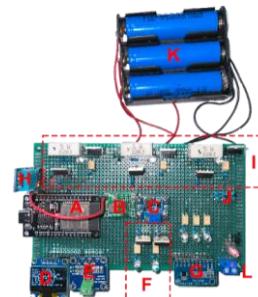
Figure 4. Prototype of the proposed BMS design

3.   RESULTS AND DISCUSSION

A comprehensive examination of the monitoring test, followed by an analysis of the balancing test and the protection test is done by using the completed prototype of the proposed BMS design. Each test will be discussed in detail, including the procedures, measurements, and observations made during the testing process. In this section, all charge MOSFET, and discharge MOSFET have been labeled as CHARGMOSFET and DISCHARGMOSFET respectively.

3.1. Monitoring test during charging

Figure 5 illustrates the overall results of battery monitoring during the charging phase. This test is done to validate that the proposed BMS design was working as intended. The battery was charged using an external power supply that supplies power to the battery with approximately 250 mA of current at 14 V. The batteries were recharged for about three and a half hours. Figure 5 shows that all the monitoring aspects of the BMS were working flawlessly, such as the reading of each cell's voltages, balancer condition, and charging MOSFET condition were recorded as section below.

(a)

(b)
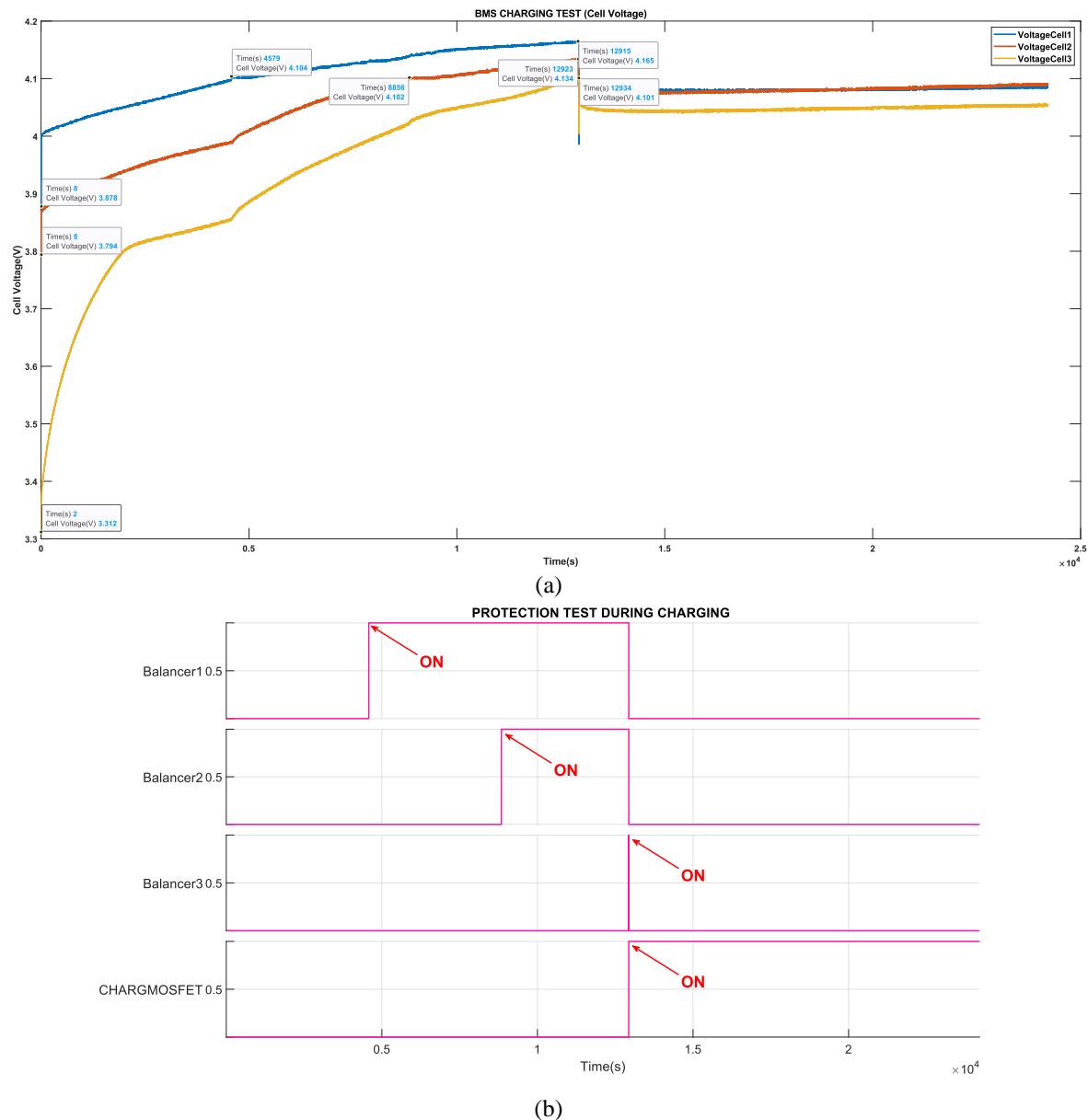
Figure 5. Protection monitoring of (a) cells voltage during charging test and
(b) balancer condition during charging

3.2. Balancing and protection test during charging

Analyzing further into the balancing test during charging can be visualized, as shown in Figure 5. The battery started charging at an initial charge of 3.88 V, 3.79 V, and 3.31 V, respectively, to each cell 1, 2, and 3. After some time, it can be seen in Figure 5(a) that Cell 1 has reached the charging limit of ≥ 4.1 V at time 4,579 s, thus triggering the condition for Balancer1 to be on the HIGH(ON) position, as can be seen in Figure 5(b) indicated by the red arrows. This condition is also met with each of the following cells such that cell 2 reaches the charge limit of ≥ 4.1 V at time 8,859 s, which triggers Balancer2 to be in the HIGH(ON) position. During this time, all the balancers work to balance the battery level using the dissipation of heat through the cement resistor (bleeding resistor) of the proposed BMS design. It also can be proven that when each resistor was at the HIGH (ON) position of the balancer, the resistor generated heat that could be felt by touching it.

Then, as can be seen in Figure 5(b) indicated by the label CHARGMOSFET graph at the bottom of Figure 5(b), it shows that the overcharging protection worked as intended. The CHARGMOSFET has been triggered to a HIGH (ON) position as soon as all the balancers are also in HIGH (ON) condition. Then, the BMS automatically cuts off the power supply to the battery to ensure no overcharging occurs. This is because the CHARGMOSFET is a PMOS that will turn off when a HIGH (1) is given to its gate pin. Figure 5(b) also shows that all the battery cells have stabilized their voltage level after the CHARGMOSFET was turned ON. Thus, the protection test for charging was a success and was able to balance and protect the batteries from overcharging.

The results and analysis of the monitoring test were conducted during the discharging process of the battery. The purpose of this test was to evaluate the accuracy and reliability of the BMS in monitoring each of the cells' voltage levels and ensuring that the system outputs a stable flow of energy to the load. Figure 6 shows the behavior of the cells during the discharging with an initial voltage level of 4.00 V for Cell 1, 3.96 V for Cell 2, and 3.86 V for Cell 3. The process takes about half an hour to complete the discharging cycle, as shown in Figure 6.
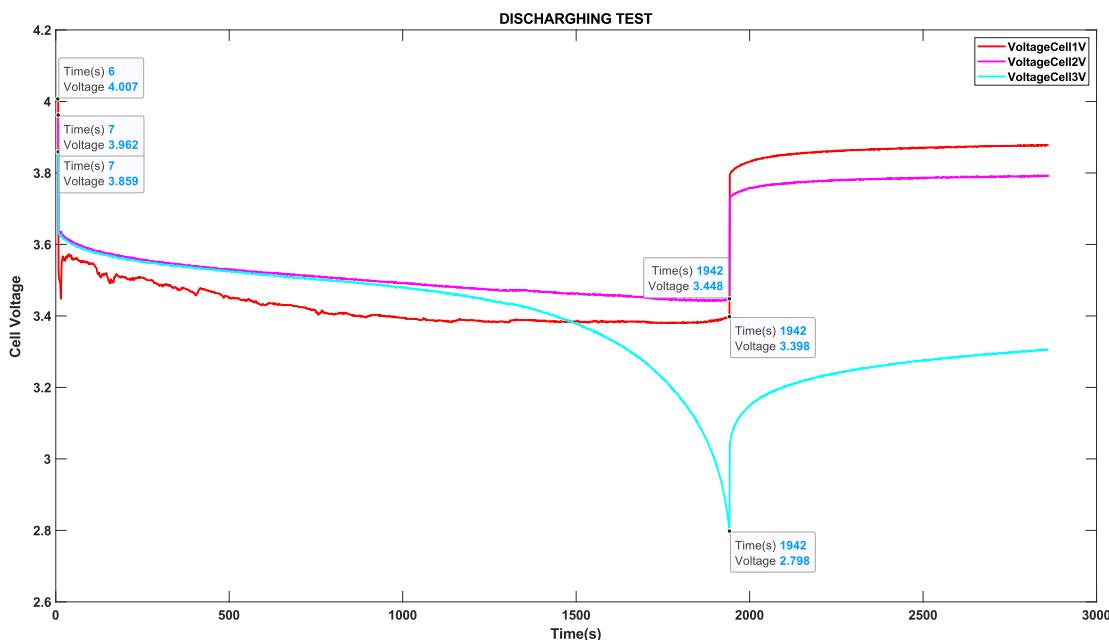

Figure 6. Cells voltage during discharging test

3.3. Protection test during discharging

Lastly, the results and analysis of the protection test conducted during the discharging process of the battery were presented in Figure 7. The main objective of this test was to assess the effectiveness of the BMS in protecting the battery against potential hazards, such as over-voltage. The test involved subjecting the batteries to approximately a 10 W load that would drain the batteries during the test.

As can be seen in Figure 7(a), the batteries have been discharged with a current measurement of 1,013 mA and with the power that measured 10,780 mW on the initial discharge. The discharging phase took about 1,945 seconds or 32.36 minutes, which triggered the auto protection system of BMS. As the graph above shows, both current and power consumption dropped to zero.

In addition to that, the auto cut-off from over discharging can be shown in detail in Figure 7(b). The graph shows that the DISCHARGMOSFET has been triggered to turn OFF the outgoing flow of current and supply to the load as soon as the condition of any one of the cells reaches below 2.80 V and as depicted in the Figure 7(b), the DISCHARGMOSFET cuts off the supply when the voltage of cell 3 reaches 2.798 V during discharging. Thus, it has been proven that the over-discharge protection system was working as intended.

(a)

(b)
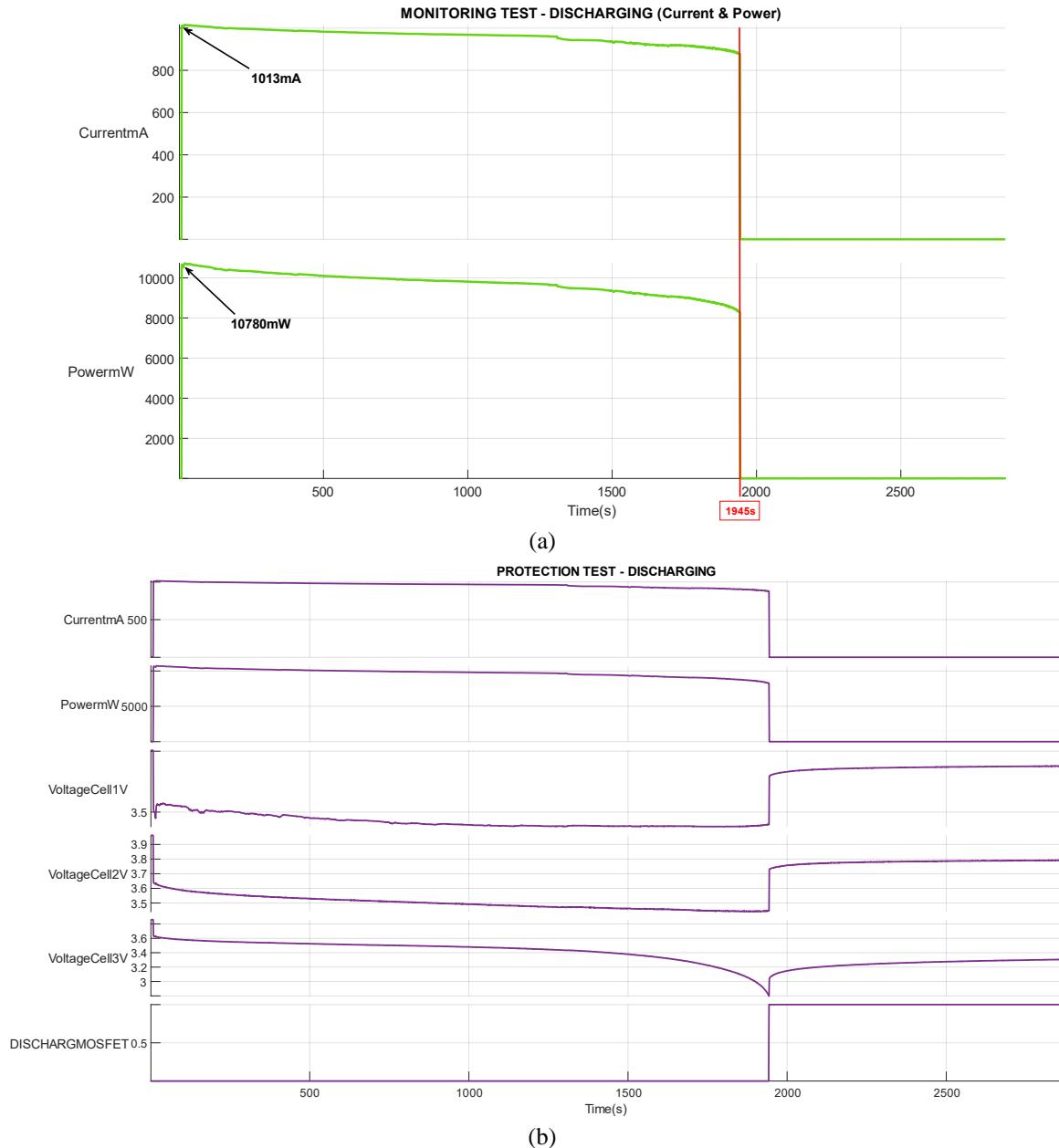
Figure 7. BMS monitoring of (a) current and power used during discharging and (b) cell voltages and discharge MOSFET during discharging

4. CONCLUSION

This project demonstrates the proposed BMS design efficiently and effectively addresses battery management obstacles. The BMS design regulates heat from higher energy cells in a battery pack to improve its performance and reduce the risk of damage. The proposed solution promotes battery technology and battery management systems in every battery application. The suggested BMS design enhances battery performance and lifespan by increasing efficiency and trustworthiness.

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